Submitted to the Astrophysical Journal

Sub-arcsecond Mid-IR Structure of the Dust Shell around IRAS 22272+5435[1]

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ABSTRACT

We report sub-arcsecond imaging of extended mid-infrared emission from a proto-planetary nebula (PPN), *IRAS* 22272+5435, performed at the MMT observatory with its newly upgraded 6.5 m aperture telescope and at the Keck observatory. The mid-infrared emission structure is resolved into two emission peaks separated by $0''.5 - 0''.6$ in the MMT 11.7 μm image and in the Keck 7.9, 9.7, and 12.5 μm images, corroborating the predictions based on previous multi-wavelength morphological studies and radiative transfer calculations. The resolved images show that the PPN dust shell has a toroidal structure with the $0''.5$ inner radius. In addition, an unresolved mid-IR excess appears at the nebula center. Radiative transfer model calculations suggest that the highly equatorially-enhanced ($\rho_{\rm eq}/\rho_{\rm pole} = 9$) structure of the PPN shell was generated by an axisymmetric superwind with $\dot{M}_{\rm sw} = 4 \times 10^{-6} M_\odot$ yr^{-1}, which was preceded by a spherical asymptotic giant branch (AGB) wind with $\dot{M}_{\rm AGB} = 8 \times 10^{-7} M_\odot$ yr^{-1}. These model calculations also indicate that the superwind shell contains larger dust grains than the AGB wind shell. The unresolved mid-infrared excess may have been produced by a post-AGB mass loss at a rate of $2 - 6 \times 10^{-7} M_\odot$ yr^{-1}. While the central star left the AGB about 380 years ago after the termination of the superwind, the star seems to have been experiencing an ambient post-AGB mass loss with a sudden, increased mass ejection about 10 years ago.

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Subject headings: circumstellar matter — dust, extinction — infrared: stars — stars: mass loss — stars: individual (IRAS 22272+5435 = HD 235858 = SAO 34504)

1. Introduction

Proto-planetary nebulae (PPNs) are evolved stars of low-to-intermediate initial mass ($0.8 - 8M_\odot$) that are in transition from the asymptotic giant branch (AGB) phase to the planetary nebula (PN) phase (e.g., Kwok 1993; Iben 1995). A PPN is a stellar system comprising of the central star of B - K spectral type surrounded by a detached circumstellar dust/gas shell. Therefore, PPNs are often bright at both optical and infrared (IR) wavelengths, resulting in the "double-peaked" spectral energy distribution (SED) - a characteristic signature of these post-AGB objects (van der Veen, Habing, & Geballe 1989; Kwok 1993). This particularly strong IR excess of a PPN is primarily due to thermal emission arising from the circumstellar dust shell, which is created by mass loss in the AGB phase.

The morphologies of the PPN dust shells are found to be predominantly axisymmetric (e.g., Ueta, Meixner, & Bobrowsky 2000 and reference therein), and such axisymmetric PPN shells are generally believed to interact with a fast post-AGB wind to form spectacularly aspherical PN shells by the time ionization of the shell material begins to take place (the interacting stellar wind model; Kwok 1982). Thus, PPN dust shells retain the most pristine, almost complete AGB mass loss histories that have not yet been altered by the interacting winds and/or energetic stellar radiation. We can, therefore, address the issues such as the cause of the morphological transformation in the circumstellar shells and the nature of the post-AGB wind by closely observing the PPN shells, especially at the innermost region of the PPN shells.

In this context, a variety of high-resolution observational techniques has been employed to observe the PPN dust shells. For example, high-resolution optical imaging has been very effective at unveiling the remarkably axisymmetric structure of the PPN reflection nebulosities (e.g., Sahai et al. 1998; Kwok, Su, & Hrivnak 1998; Su et al. 1998; Hrivnak et al. 1999; Ueta, Meixner, & Bobrowsky 2000). While such optical images of superb resolution uncovered detailed geometrical information of the PPN shells, optical emission, i.e., dust-scattered star light, allows only an indirect probe of the dust mass distribution. Therefore, mid-IR imaging, which directly probes the mass distribution through thermal emission arising from dust grains, has also been employed (e.g., Skinner et al. 1994;

[1]The observational data presented here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution, and at the W. M. Keck Observatory, which was made possible by the generous financial support of the W. M. Keck Foundation and is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration.

Meixner et al. 1997, 1999). However, the diffraction-limited nature of mid-IR observations permits imaging only at marginal ($\sim 1''$) resolution with existing 3m class IR telescopes.

With large aperture telescopes coming on-line, it is now becoming possible to obtain sub-arcsecond resolution mid-IR images (e.g., Jura & Werner 1999; Jura, Chen, & Werner 2000; Morris & Sahai 2000) which would further improve our understanding of the axisymmetric shaping in post-AGB objects. In this paper, we report sub-arcsecond mid-IR imaging of a PPN, *IRAS* 22272+5435, and the results of 2-D radiative transfer calculations based on the spatial information obtained from the high-resolution mid-IR images.

2. The Object: *IRAS* 22272+5435

IRAS 22272+5435 (= HD 235858 = SAO 34504; hereafter *IRAS* 22272) was identified as a PPN candidate soon after its detection by the *Infrared Astronomical Satellite* (*IRAS*) because of the fairly bright nature both in the optical ($V = 8.9$) and IR (Pottasch & Parthasarathy 1988). Subsequent spectroscopic observations classified the central star as G5 and revealed its carbon-rich (C−rich) nature through molecular carbon features (Hrivnak & Kwok 1991; Hrivnak 1995). The C−rich nature of the source was also shown by detection of various carbon-bearing molecular species (Lindqvist et al. 1988; Omont et al. 1993) and the IR hydrocarbon features (Buss et al. 1990; Geballe et al. 1992; Justtanont et al. 1996). Moreover, Začs, Klochkova, & Panchuk (1995) have recently revealed an extremely C−rich nature (C/O $\sim$ 12) of the source by high-resolution spectroscopic observations.

In addition to the IR hydrocarbon features at around $5-13$ μm, *IRAS* 22272 is known to have strong IR features near 21 and 30 μm, whose carrier species have not been firmly identified. The 21 μm feature was originally discovered as a result of an investigation in the *IRAS* low resolution spectrometer (LRS) database (Kwok, Volk, & Hrivnak 1989), and subsequent investigation found that the 21 μm feature seemed to be a unique feature of C−rich PPNs (Kwok, Volk, & Hrivnak 1999). A recent *ISO* spectroscopic survey of the 21 μm sources has determined the intrinsic shape of the feature that would suggest the solid-state nature of the carrier species (Volk, Kwok, & Hrivnak 1999). However, the origin of the feature remains elusive despite a number of suggestions for its carrier species (e.g., Begeman et al. 1996; Justtanont et al. 1996; Hill, Jones, & d'Hendecourt 1998; von Helden et al. 2000). The 30 μm feature was discovered by Omont et al. (1995) during their spectroscopic surveys of C−rich PPNs to look for additional IR features which would help to identify the 21 μm feature. The 30 μm feature in *IRAS* 22272 is enormous and the integrated flux over the feature accounts for roughly 20% of the bolometric luminosity (Omont et al. 1995). Because the 30 μm feature is also seen in C−rich AGB stars and PNs, the 30 μm does not seem to share the transient nature of the 21 μm carrier species. The identification of the 30 μm carrier species is also still incomplete: suggested species include, for example, MgS (Goebel & Moseley 1985) and a mixture of hydrocarbons (Duley 2000).

Morphologies of *IRAS* 22272 have been studied previously at various wavelengths. Meixner et al. (1997) and Dayal et al. (1998) presented mid-IR images at arcsecond resolution which showed clear elongation in the emission core. These authors respectively suggested the presence of an inclined dust torus or a disk by means of radiative transfer calculations and the color temperature and optical depth maps derived from the source images. High-resolution optical images obtained by *Hubble Space Telescope* (*HST*) revealed a reflection nebulosity of very faint surface brightness with a clear view of the central star at the center of the nebula (Ueta, Meixner, & Bobrowsky 2000). The optical nebulosity was largely elongated perpendicular to the core elongation seen at the mid-IR, suggesting that the preferred directions of the dust-scattered star light are defined by the biconical openings of the suspected dust torus. A recent near-IR imaging by Gledhill et al. (2000) was able to separate polarized (i.e., dust-scattered) emission arising from the dust grains from the unpolarized direct stellar emission by means of imaging polarimetry. Their J band polarized flux image showed a ring-like structure embedded in an elongated halo, corroborating the findings of the mid-IR and optical imaging.

Based on the combined results of our recent mid-IR and *HST* imaging surveys of PPNs (Meixner et al. 1999; Ueta, Meixner, & Bobrowsky 2000), *IRAS* 22272 is morphologically classified as a SOLE-toroidal PPN. The SOLE-toroidal morphological type is considered to be caused by an optically *thin* dust torus: the dust-scattered star light is only marginally confined in the biconical openings thereby forming an elliptically elongated optical nebulosity with a clear view of the central star in the middle of the nebula, while the mid-IR thermal emission from dust grains shows some evidence for the central dust torus through either an elongation of the core or two emission peaks when resolved (e.g., Figure 5 of Ueta, Meixner, & Bobrowsky 2000). Especially important is the resolved two-peak structure of the mid-IR emission core because these peaks are manifestations of the limb-brightened edges of an optically *thin* dust torus, acting as the direct evidence for the toroidal dust distribution in the PPN shell. However, because of the diffraction-limited mid-IR imaging and the intrinsically compact nature of the PPN dust shells, only 22 out of 72 PPNs have been resolved in the mid-IR so far. Moreover, there have been only two out of 11 SOLE-toroidal PPNs in which the central dust torus is well-resolved to show two limb-brightened peaks in the mid-IR emission core[8].

Now, *IRAS* 22272 is known to have the largest elongated emission core ($1''.6$ diameter at 11.8 μm; Meixner et al. 1997) among the SOLE-toroidal PPNs in which the two-peak core structure has not been resolved. Using the arcsecond resolution images, Meixner et al. (1997) have estimated the inner radius of the central dust torus to be about $0''.6$ by 2-D radiative transfer calculations. Therefore, *IRAS* 22272 is the prime target PPN for the mid-IR imaging at sub-arcsecond resolution with a large aperture telescope, and we conducted imaging of the source at the MMT and W. M. Keck Observatories using two mid-IR cameras in order to resolve the yet unresolved two limb-

[8]These two cases are *IRAS* 17436+5003 (Skinner et al. 1994) and *IRAS* 07134+1005 (Meixner et al. 1997; Jura, Chen, & Werner 2000). See also Figure 5 of Ueta, Meixner, & Bobrowsky (2000).

brightened edges in the emission core. Recently, the presence of more than one emission peaks has been tentatively confirmed by an 8.8 μm image taken at the Keck telescope which shows two peaks in the mid-IR emission nebula (Morris & Sahai 2000).

3. Sub-arcsecond Mid-IR Imaging and Results

3.1. Observations and Data Reduction

We observed *IRAS* 22272 at the MMT observatory on 2000 June 16 during the engineering/commissioning period that followed its successful first-light on 2000 May 17 after the primary mirror conversion (West et al. 1997). The observations were made under clear sky with the University of Arizona/Smithsonian Astrophysical Observatory Mid-IR Array Camera (MIRAC3; Hoffmann et al. 1998) interfaced with the University of Arizona BracewelL Infrared Nulling Cryostat (BLINC; Hinz et al. 1998) mounted at the Cassegrain focus of the upgraded 6.5m primary mirror. The MIRAC3 array is a Boeing HF-16 arsenic-doped silicon blocked-impurity-band hybrid array and has a 128×128 pixel format, which would give a $19'' \times 19''$ field of view with the $0''.15$ pixel scale. The object was observed with 10% bandwidth ($\Delta\lambda/\lambda = 0.1$) filters at 8.8, 9.8 and 11.7 μm without the BLINC nulling mode.

Because the f/9 secondary - the only available secondary for the commissioning period - was not capable of chopping or tip-tilt, a nod-only beam-switching was used with an elevation nod throw of $9''$, which yielded two on-chip sky-subtracted images of the source in a single integration cycle. The telescope was experiencing a drift in the azimuth direction with a rate of approximately $0''.2$ min^{-1} in spite of its excellent pointing accuracy. Therefore, we were limited to the maximum integration time of 10 sec to prevent images from being spuriously elongated. The nod wait was set to $10 - 12$ sec to allow the telescope to settle after each nodding, and this resulted in a typical duty cycle of about 50%.

The resulting multiple sets of beam-switched on-chip images were individually derotated with respect to each other and then co-added into a final image of size $\sim 10''$ across. The relative shifts among images were calculated using a cross-correlation routine. Each image was subdivided by 4×4 pixels before derotation to make the pixel scale of $0''.0375$/pix for accurate registration. The total integration times of the final images are 200 sec for 8.8 and 9.8 μm and 100 sec for 11.7 μm, resulting in 1 σ rms noise of 28, 41, and 107 mJy arcsec^{-2} respectively at 8.8, 9.8, and 11.7 μm. For point-spread-function (PSF) and flux calibration, we observed β Peg (a CGS3 standard; Cohen & Davies 1995) before and after the object to check for variations in the PSF. The PSF sizes defined by the full width at half maximum (FWHM) are $0''.49$, $0''.51$, and $0''.55$ at 8.8, 9.8, and 11.7 μm, respectively. These values define the observed seeing-limited resolution. Upon flux calibration, the images were corrected for atmospheric extinction using the averaged correction factors derived from the standard star observations made at various airmasses throughout the night. The source flux densities (Jy) at the observed wavelengths were derived by scaling the standard flux densities at

the corresponding wavelengths. Absolute flux calibration errors are estimated to be approximately $\pm 5\%$. A detailed description of the general MIRAC data reduction and flux calibration processes is given by Meixner et al. (1999).

We also obtained images of *IRAS* 22272 observed with the MIRLIN mid-IR camera (Ressler et al. 1994) mounted at the f/40 bent Cassegrain visitor port of the Keck II Telescope. The MIRLIN uses a 128×128 Si:As array with a plate scale of $0''137$ pix^{-1} for a total field of view of $17'' \times 17''$. The observations were carried out on 2000 November 4 under partly cloudy sky. The object was imaged with an 8% bandwidth filter at 7.9 μm (N0) and 10% bandwidth filters at 9.7 (N2) and 12.5 μm (N5). The use of a nod-chop beam-switching with the N-S nod throw of $7''$ and E-W chop throw of $7''$ resulted in four on-chip sky-subtracted images of the target in a single integration cycle. The resulting multiple sets of images were derotated and co-added into a final image by using the same routines as the MMT data reduction. For the purpose of further data analysis, the individual on-chip images were subdivided prior to derotation so that the final images would have the same pixel scale as the MMT images. The total integration times of the final images are then 240, 192, and 150 sec respectively for 7.9, 9.7, and 12.5 μm. β And (a CGS3 standard; Cohen & Davies 1995) was observed before the source observations for the calibration purposes. However, we were unable to flux calibrate the data due to the non-photometric sky conditions of the night: we used the Keck images only in qualitative analyses in the following. The PSF sizes are measured to be $0''.37$, $0''.30$, and $0''.37$ respectively at 7.9, 9.7, and 12.5 μm. Table 1 summarizes the observations along with measured quantities to be discussed in the following sections.

3.2. Sub-arcsecond Mid-IR Morphology

3.2.1. Structure of the Mid-IR Nebula

Images of *IRAS* 22272 and corresponding PSFs obtained at both observatories are displayed in Figure 1. The difference in resolution between the telescopes is readily recognized by the PSF sizes. The mid-IR emission regions of *IRAS* 22272 consists of two major parts: the extended halo ($\lesssim 40\%$ of the peak intensity) and emission core ($\gtrsim 40\%$ of the peak intensity). The emission halo is roughly circular with radius of about $1''$ at the 10% of the peak intensity for all wavebands. Although not apparent in Figure 1, a faint emission halo can be traced out to at least $3''$ from the center at the full width at zero intensity. In order to align images that were obtained at two observatories with different resolution, we first defined the nebula center by taking advantage of the circular shape of the emission halo. We fit the emission halo with elliptical isophotes and determined the nebula center by averaging the central coordinates of the isophotes with $20 - 40\%$ of the peak intensity. This particular isophotal intensity range was adopted to avoid influences from any core structure ($\lesssim 40\%$) while keeping the surface brightness of the halo itself reasonably high in order to fit the halo shape accurately ($\gtrsim 20\%$): the 20% of the peak intensity translated into a signal-to-noise (S/N) ratio of at least 50 in these images. The images presented in Figure 1 have been centered at

the nebula center.

Within the circular halo, the emission core is clearly resolved into a two-peaked structure in the MMT image at 11.7 μm and all three Keck images at 7.9, 9.7, and 12.5 μm with the separation of the peaks varying from $0''.44$ to $0''.62$. However, the 8.8 and 9.8 μm MMT images show merely a single peak. Irrespective of the detailed structure, the emission core shows an overall elongation (the averaged ellipticity: 0.14) in the NE-SW direction with the position angle (PA) about 55° (to E from N), which is consistent with the previous observations at arcsecond resolution (Meixner et al. 1997; Dayal et al. 1998). The present observations at sub-arcsecond resolution additionally show a dent at the SE side of the elongated core in all wavebands, making the emission core "kinked" towards the NW direction. The two emission peaks are located at each end of the "kinked" core, almost diametrically positioned with respect to the nebula center. The overall appearance of the mid-IR nebula thus seems symmetric with respect to a fiducial line with a PA of $\sim -35°$, which is perpendicular to the direction of the general core elongation.

3.2.2. Structure of the Emission Core

The two-peaked morphology at the innermost core is just as expected from the SOLE-toroidal morphological classification of *IRAS* 22272 (Meixner et al. 1997; Ueta, Meixner, & Bobrowsky 2000) and agrees well with the other two SOLE-toroidal type PPNs, *IRAS* 07134+1005 and *IRAS* 17436+5003, in which the two-peaked core structure was resolved in the mid-IR (See Figure 5 of Ueta, Meixner, & Bobrowsky 2000). However, the kinked core shape is unique to *IRAS* 22272 and was not observed in the other two SOLE-toroidal type PPNs. While an intermediate inclination angle[9] ($\theta_{\rm incl} \gtrsim 45°$) was suggested for the central dust torus in those two PPNs (Meixner et al. 1997; Meixner, Ueta, & Bobrowsky 2001, respectively), a less tilted inclination ($\theta_{\rm incl} = 30° - 40°$) was proposed for *IRAS* 22272 based on the morphology of a color temperature map (Dayal et al. 1998). A smaller $\theta_{\rm incl}$ would probably introduce such a kinked core morphology due to a difference in column densities along the different lines of sight in the nebula. Thus, the mid-IR morphology of *IRAS* 22272 would indeed be manifestations of the limb-brightened edges of the central dust torus whose axis of symmetry lies along a PA of about $-35°$ in the plane of the sky.

The emission core structure also shows dramatic changes as the waveband shifts. At 7.9 μm, the peak separation is $0''.44$ and the NE peak is about 40% brighter than the SW peak. As one moves to longer wavebands, the separation increases while relative brightness of the NE peak with respect to the SW peak decreases. Especially remarkable is that the SW peak becomes brighter than the NE peak at 12.5 μm. These changes are well demonstrated by the normalized emission profiles across the direction of the general core elongation shown as Figure 2. The Keck images

[9]The inclination angle of the dust torus, $\theta_{\rm incl}$, is defined to be the acute angle between the line of sight and the pole.

suggest that the peak separation at 8.8 and 9.8 μm would be roughly $0''.45$, which is smaller than the MMT PSF size at these wavelengths ($\sim 0''.5$). This is why the MMT images at 8.8 and 9.8 μm were unable to resolve the core structure. The unresolved nature of the MMT images at lower wavebands is also seen in the emission profile (Figure 2) as the barely resolved profile being blended into one structure peaking closer to the nebula center. A further inspection of Figure 2 also reveals that the location of the NE peak shifts farther away from the nebula center at longer wavebands (at 11.7 and 12.5 μm) while the SW peak seems anchored at the same position. This shift is caused primarily by the NE peak that increased its brightness at the lower wavebands.

The central star can be bright enough to contribute significantly to the total flux at $\lesssim 10\mu m$ in the case of an optically thin dust shell. The proximity of the dominant NE peak to the nebula center in the 7.9 and 9.7 μm image is very suggestive that the central star is indeed responsible for this unique emission characteristics of the nebula. In the optically thin approximation, we can derive a color temperature map by taking a ratio of images at two wavebands (e.g., Hora et al. 1996; Dayal et al. 1998). Such color temperature maps can be used to infer the location of the central star from the distribution of the warmest dust grains (e.g., Ueta et al. 2001). The color temperature maps derived from the MMT images showed a single peak between the NE peak and the nebula center: these three points (the NE peak, the nebula center, and the dust temperature peak) are coincident with each other within the resolution of the images. The color temperature maps derived from the uncalibrated Keck images yielded a qualitatively similar result, confirming this finding.

3.2.3. Structure of the Dust Shell

In order to recover the emission structure by the dust shell alone, we removed the central stellar emission component from the total nebula emission by means of (1) PSF subtraction and (2) deconvolution. PSF subtraction was done first by estimating the stellar flux at the wavelengths of observation from the Rayleigh-Jeans tail of the blackbody curve fitted with existing near-IR photometry (Manchado et al. 1989; van der Veen, Habing, & Geballe 1989; Hrivnak & Kwok 1991) including our own[10], and then, by subtracting the scaled PSF images from the observed images. The PSF subtracted images are displayed in the top frames of Figure 3 (labeled as "Sub"). The central stellar contribution to the total flux turned out to be at most 6% (Table 1), and the structure of the mid-IR nebula was virtually unchanged. We then performed Richardson-Lucy deconvolution to remove the PSF effects from the "raw" images and the results are presented in the bottom frames of Figure 3 (labeled as "Decon"). The deconvolved 11.7 μm image clearly recovered the limb-

[10] *IRAS* 22272 was observed on 1999 November 16 under photometric conditions with NIRIM (Meixner, Young Owl, & Leach 1999) at Mt. Laguna observatory, which is jointly operated by the University of Illinois at Urbana-Champaign and the San Diego State University. See Table 1. For more details on data reduction, see Ueta et al. (2001).

brightened edges of the dust torus that were symmetrically located with respect to the relatively emission-free nebula center.

The orientation of the limb-brightened edges of the dust torus agrees very well with the direction of the suspected axis of symmetry of the dust torus along a PA of about $-35°$, which was also suggested by the elongation of the optical and near-IR reflection nebulosity (Gledhill et al. 2000; Ueta, Meixner, & Bobrowsky 2000). Figure 4 shows the V band HST image (Ueta, Meixner, & Bobrowsky 2000) overlaid with contours of the deconvolved 11.7 μm image. Aside from the detailed shapes, the directions of a general elongation in the optical (PA $\sim -40°$) and mid-IR (PA $\sim 50°$) appear to be perpendicular, supporting the idea that the toroidal dust shell would define the "waist" of the reflection nebulosity. Although stellar photons basically can go all directions in case of the optically thin dust shell of *IRAS* 22272, its dust torus is still capable of shaping the optical reflection nebulosity according to its dust density distribution. The HST image of *IRAS* 22272 shows four elliptical tips with the bottom two (along PAs of $\sim 155°$ and $-75°$) being more extensive than the other two. Interestingly, the directions of these optical protrusions are strikingly coincident with the directions in which there is less amount of dust grains: the largest elliptical protrusion towards SE is coincident with one of the bicone openings for the dust torus and other protrusions towards W and N seem to correspond with the "breaks" of the dust distribution as indicated by the arrows in Figure 4. These consistencies with images at other wavelengths strongly suggest that the dust shell assumes a toroidal shape and its axis of symmetry is oriented along PA of $\sim 155°$.

3.2.4. Non-Stellar Emission Component

On the contrary, neither PSF subtraction nor deconvolution successfully removed the emission component at the nebula center at 8.8 and 9.8 μm. Instead, the deconvolved images at these wavebands even indicated the dominance of the central emission in the entire mid-IR emission regions. Thus, we deconvolved the PSF subtracted images at these wavebands. The deconvolved, PSF-subtracted image at 9.8 μm recovered the dust shell structure that was free of the central emission. This would indicate that the PSF subtraction had already removed the stellar emission component successfully. However, the deconvolved, PSF subtracted image at 8.8 μm still displayed a dominant central peak. These results could suggest that the remaining central emission after both PSF subtraction and deconvolution represents an emission component of non-stellar origin, that is, there is distribution of dust grains in the inner cavity of the dust shell. The existence of such an emission component would require post-AGB mass ejection processes. In fact, such a post-AGB mass loss has been already suggested by the observed change of the near-IR CO emission features into absorption features, indicating the onset of a sudden mass ejection (Hrivnak, Kwok, & Geballe 1994).

4. 2-D Radiative Transfer Modeling

4.1. Basic Description

The mid-IR images at sub-arcsecond resolution revealed evidence for the toroidal dust distribution at the inner edge of the PPN shell of *IRAS* 22272. The images also suggested a rather small inclination angle of the shell ($\theta_{\rm incl} = 30^\circ - 40^\circ$) and a possible presence of post-AGB ejecta in the inner cavity of the PPN shell. We can quantify the axisymmetric nature of the dust shell with the help of the spatial information yielded from these high-resolution mid-IR images. To achieve this goal, we performed radiative transfer calculations with a code which solves the equation of radiative transfer in a fully two-dimensional grid using a method developed by Collison & Fix (1991). This code has been used to model axisymmetric circumstellar dust shells around evolved stars (Meixner et al. 1997; Skinner et al. 1997; Ueta et al. 2001; Meixner, Ueta, & Bobrowsky 2001). In particular, *IRAS* 22272 was previously modeled with an earlier version of the code using mid-IR images at arcsecond resolution showing only the unresolved core. The model calculations predicted the inner shell radius ($R_{\rm in}$) to be $0''.6$ (Meixner et al. 1997) despite the lack of detailed spatial information. Interested readers are encouraged to refer to Meixner et al. (1997) and Skinner et al. (1997) for the detailed description of the code and Ueta et al. (2001) for more discussions on the iteration and parameter fitting processes.

Following Meixner et al. (1997), the circumstellar dust shell in our model calculations is assumed to be a result of a two-phased AGB mass loss process: a spherically symmetric AGB wind (phase 1) gradually transforming into an axisymmetric superwind (phase 2) in the late AGB phase. In this model, an axisymmetric superwind shell (i.e., the central torus) of size $R_{\rm sw}$ is surrounded by a spherical AGB shell of size $R_{\rm out}$, and the degree of axisymmetry for the entire dust shell is controlled by five geometric parameters in the density profile, $\rho(r,\theta)$, and the opening angle of the biconical cavities (θ_0), in which dust density can be set arbitrarily. The main physical processes, i.e., dust absorption, emission, and (isotropic) scattering, are treated at zone centers in the 2-D grid by calculating the optical properties for a given dust composition evaluated with Mie theory. To account for the near-IR hydrocarbon features seen in the spectrum of *IRAS* 22272 (Buss et al. 1990; Geballe et al. 1992; Justtanont et al. 1996), we adopted the optical constants of hydrogenated amorphous carbons (HACs; type BE of Colangeli et al. (1995) and Zubko et al. (1996)) and aimed at fitting the overall shape of the continuum emission in the SED. The use of HACs to simulate dust continuum emission in *IRAS* 22272 is warranted because *IRAS* 22272 is known to show especially strong 3.4 and 6.9 μm features which arise from the $-{\rm CH}_{2,3}$ functional groups (e.g., Buss et al. 1993; Duley 2000).

Starting with the initial parameters adopted from the previous calculations and other references in the literature (Meixner et al. 1997 and references therein), the best-fit model parameters are sought iteratively by fitting the shape of the SED as well as the projected 2-D morphology of the model. The major differences between our model calculations and the previous ones by Meixner et al. (1997) are that (1) $R_{\rm in}$ is practically an input parameter provided by the images with the

resolved core structure (Figure 1 and 3), (2) the code now allows a distribution of grain sizes of the form $n(a) \propto a^{-3.5} \exp(-a/a_0)$ (Kim, Martin, & Hendry 1994; Jura 1994), in which a is the grain size and a_0 is an exponential scaling factor acting as the "effective" maximum grain size, and (3) when applicable (i.e., $2\pi a/\lambda \ll 1$), the assumption of the continuum distribution of ellipsoids (Bohren & Huffman 1983) is used for the particle shape distribution. Especially, having $R_{\rm in}$ as an input parameter is the major strength in our model calculations. The temperature of the dust shell, $T_{\rm dust}$, is essentially defined by $R_{\rm in}$, and therefore, the energetics of the dust shell heating is constrained fairly well in our model calculations compared with other radiative transfer models in which $R_{\rm in}$ needs to be iteratively searched by fitting only with the shape of the SED. We adopted $0''.5$ as the initial $R_{\rm in}$ from the deconvolved images (Figure 3). The use of the high-resolution mid-IR images in the model fitting process is robust because the geometrical parameters of the dust shell, especially the inclination angle ($\theta_{\rm incl}$) and biconical opening angle (θ_0), are rather sensitive to the morphology of the 2-D projected model images. The dust size distribution also plays an important role in determining the best-fit parameters because $R_{\rm in}$ is now observationally constrained and the energetics of dust heating can be affected by different size distributions.

4.2. The Best-Fit Model

The best-fit model for the dust shell of *IRAS* 22272 consists of the central star ($T_{\rm eff} \sim 5800$ K) surrounded by two separate sets of dust shells representing a PPN shell (AGB wind shell + superwind shell) and a post-AGB wind shell located in the inner cavity of the PPN shell. The PPN shell has the inner radius of $R_{\rm in} = 0''.5$ and consists of the inner, superwind shell of radius, $R_{\rm sw} = 5 \times R_{\rm in}$, and the outer, AGB wind shell of radius, $R_{\rm out} = 24 \times R_{\rm in}$. The superwind shell is highly equatorially-enhanced ($\rho_{\rm eq}/\rho_{\rm pole} = 9$) as opposed to the generally spherical AGB wind shell. The total PPN shell size ($R_{\rm out}$) is strictly an assumption based on the known extent of ^{12}CO emission (e.g., Fong et al. 2000) and needs to be constrained by future far-IR and/or sub-mm observations. Within the inner cavity of the PPN shell, there is another set of shells which account for a possible presence of the post-AGB ejecta. For simplicity, the post-AGB shell is assumed to have a similar two-layer structure as the PPN shell of the radius $R_{\rm in}$ (i.e., filling the inner cavity of the PPN shell), in which the majority of ejecta is thought to be concentrated within a thin shell defined by the boundaries at $R_{\rm in}^{\rm pAGB} = 0''.075$ and $R_{\rm out}^{\rm pAGB} = 1.2 \times R_{\rm in}^{\rm pAGB}$. The dust size distribution is slightly different in the superwind shell and the AGB wind shell, i.e., a population of large particles is weighted more in the superwind shell ($a_0 = 10\ \mu m$) than in the AGB wind shell ($a_0 = 0.1\ \mu m$). In the post-AGB shell, the dust size distribution is set to be the same as in the superwind shell for simplicity.

Because both the luminosity of the central star and the dust shell size scale with the square of distance to the source, model calculations would not be able to fix the distance by the iterative fitting. Therefore, we adopted 1.6 kpc as the distance to *IRAS* 22272 from a recent model calculations (Szczerba et al. 1997) and estimates (Yuasa, Unno, & Magono 1999; J. Nakashima 2000

priv. comm.). The adopted distance yields $L_* \sim 1.3 \times 10^4 L_\odot$ for the luminosity of the central star, $R_{\rm in} = 1.2 \times 10^{16}$ cm, $R_{\rm sw} = 6.0 \times 10^{16}$ cm, and $R_{\rm out} = 2.9 \times 10^{17}$ cm for the PPN shell, and $R_{\rm in}^{\rm pAGB} = 1.8 \times 10^{15}$ cm, and $R_{\rm out}^{\rm pAGB} = 2.1 \times 10^{15}$ cm for the post-AGB shell. These shell sizes would suggest the dynamical age of the shell to be about 380 years, assuming the constant expansion velocity of 10 km s^{-1} (Zuckerman & Dyck 1986; Lindqvist et al. 1988; Woodsworth, Kwok, & Chan 1990; Omont et al. 1993), and the AGB and superwind mass loss rates as $\dot{M}_{\rm AGB} = 7.8 \times 10^{-7}$ and $\dot{M}_{\rm sw} = 4.1 \times 10^{-6} M_\odot$ yr^{-1} and the post-AGB mass loss rate as $2 - 6 \times 10^{-7} M_\odot$ yr^{-1}, assuming a dust-to-gas mass ratio of 4.5×10^{-3}, an approximate value used for C−rich AGB stars (Jura 1986). Table 2 summarizes the parameters and derived quantities for the best-fit model.

Figure 5 shows the best-fit SED for our model calculations. The total SED consists of the PPN shell contribution and the post-AGB shell contribution. The *Infrared Space Observatory* (*ISO*) spectrum[11] and other photometric data (Manchado et al. 1989; van der Veen, Habing, & Geballe 1989; Hrivnak & Kwok 1991; García-Lario et al. 1997; Meixner et al. 1997; Dayal et al. 1998, *IRAS* fluxes, and present observations) are shown for comparison. As the *ISO* spectrum shows, *IRAS* 22272 is full of strong IR features on the blueward shoulder and near the dust peak (the far-IR spikes appearing in the LWS data at ~ 200 μm seem to be instrumental), and it is difficult to define the continuum: we assumed fluxes at around 15 and 60 μm represented the continuum. The 1.3 mm continuum flux is strictly a lower limit because the observed beam size ($11''$) is smaller than the known extent of the molecular envelope (e.g., ^{12}CO shell of $18''$ diameter; Fong et al. 2000). *IRAS* 22272 is visually known as a variable star and the variation is indicated by the optical photometry done over two epochs (Hrivnak & Kwok 1991), each of which is connected by a thin line. The interstellar extinction has been taken into account and the best-fit model suggests $A_{\rm v} = 2.5$, which is slightly higher than the observed value along the line of sight toward *IRAS* 22272 for the adopted distance, 1.6 kpc (Neckel & Klare 1980).

Figure 6 shows the 2-D projected images for our best-fit models at 8.8, 9.7, and 11.7 μm. To create these images, we convolved only the PPN shell model images with the observed PSF images. By inspection, one immediately sees that emission at the nebula center is lacking in model images at 8.8 and 9.8 μm. This is due to the fact that the post-AGB shell model was not included, and is consistent with the inference from the observations that emission near the nebula center at lower wavebands arise from the post-AGB ejecta located in the inner cavity of the PPN shell. The whole shell system has biconical openings of 20° along the axis of symmetry with an inclination of $\sim 25°$ from the pole-on orientation, and the near side of the biconical openings points to the SE direction (PA of 150°). The resulting morphologies become extremely sensitive to the $\theta_{\rm incl}$ and θ_0 pair when the dust shell is optically thin as *IRAS* 22272 and would completely be altered if, for example, $\theta_{\rm incl}$ is changed by more than $\sim 10\%$.

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[11]The spectrum is constructed by combining the pipeline-calibrated SWS and LWS data available at the *ISO* archive (http://www.iso.vilspa.esa.es/ida/index_us.html).

4.3. The Energetics of Dust Shell Heating

For our model calculations, we first adopted the dust size distribution, $n(a) \propto a^{-3.5} \exp(-a/a_0)$, with $a_0 = 0.1$ μm for the entire PPN shell, based on the study of the particle size distribution around a well-known carbon star, IRC+10 216 (Jura 1994). This dust distribution, however, yielded the SED whose dust peak was too blue, i.e., $T_{\rm dust}$ was too high. This SED is shown in Figure 4 as a thin dotted line for comparison. In typical radiative transfer calculations, $R_{\rm in}$ would then be iteratively increased to decrease $T_{\rm dust}$ (i.e., to shift the dust peak redward). Because $R_{\rm in}$ was already well-constrained to be around $0''.5$ by the mid-IR images, increasing $R_{\rm in}$ would not be a desirable option in our iterations. In Mie theory, the scattering and absorption coefficients are respectively proportional to $(a/\lambda)^4$ and a/λ if a/λ is sufficiently small, that is, smaller particles are generally more absorptive than larger particles. Therefore, increasing a_0 is physically equivalent to decreasing the efficiency of dust absorption, and the energetics of dust shell heating can be controlled by adjusting the efficiency of dust absorption, i.e., a_0.

We then iteratively changed a_0 in both of the superwind and AGB wind shells and converged to the best-fit model (thick dashed line), in which the superwind shell has a larger population of big grains ($a_0 = 10$ μm) than the AGB wind shell ($a_0 = 0.1$ μm) while $a_{\rm min}$ is kept at the best-fit value of 10 $\AA$. Upon iterating on the size distribution, we simply assumed that any change of size distribution would concurrently occur with the change of the mass loss geometry. The superwind shell is thus made slightly inefficient in absorbing the stellar UV/optical photons, effectively reducing $T_{\rm dust}$ at $R_{\rm in}$. In the AGB wind shell, there is now more abundant UV/optical photons that have been scattered through the superwind shell, and this excess population of UV/optical photons contributes to an additional heating of the AGB wind shell increasing the total far-IR flux. The population of small particles in the AGB wind shell is thus necessary as the absorbers of stray UV/optical photons to be an additional source for the dust shell heating. If a_0 is set to 10 μm in the AGB wind shell, for example, the dust heating would become too inefficient and there would not be enough IR flux to fit both of the blueward shoulder and redward tail of the observed dust peak.

One would intuitively think that larger grains are typically found in the inner region of the dust shell, where density is highest, and that such large grains would be sputtered into smaller pieces as they coast away from the central star. Such an intuitive view was theoretically confirmed by hydrodynamical calculations of a self-consistent dust-driven wind model for a C−rich star (Dominik, Gail, & Sedlmayr 1989). Furthermore, Krüger & Sedlmayr (1997) found that grain drift significantly reduce the grain distribution at large grain sizes, and the effect was found to be more pronounced in winds with lower mass loss rates. These results are consistent with our best-fit model in which an enhanced population of large dust grains is found in the superwind shell, where dust density and mass loss rates are higher.

4.4. The Post-AGB Shell

The observed dust peak is enormous due to the strong IR features that are seen between $20-30$ μm in the *ISO* spectrum. If we fit the shape of the dust peak using the assumed continuum at around 15 and 60 μm, the PPN shell model alone would significantly underestimate fluxes at these wavelengths (see the difference between the *ISO* spectrum and thick dashed line at around $5-10$ μm). Although some flux underestimate in this region of the spectrum is expected due to lack of proper identification of the dust feature carriers, the resulting flux underestimate seems too severe to be accounted for just by the insufficient knowledge of dust composition in the PPN shell.

Therefore, we also performed radiative transfer calculations for a post-AGB shell - distribution of mid-IR emitting material located in the inner cavity of the PPN shell - as suggested by the centrally concentrated core morphology observed in the lower waveband images. The ultra-sub-arcsecond structure of the post-AGB shell can not be determined from our mid-IR images and the nature of a post-AGB mass ejection is generally not well understood. To date, there is only one observational suggestion for the post-AGB mass ejection in *IRAS* 22272, in which the CO emission features transformed into absorption features about a decade ago (Hrivnak, Kwok, & Geballe 1994). Thus, we simply assumed that an ambient post-AGB mass loss continued since the termination of the superwind and a sudden mass ejection took place about 10 years ago. The width of the post-AGB shell is then determined by assuming any mass loss would result in an expansion at the rate of 10 km s^{-1} (observed CO expansion velocity; Woodsworth, Kwok, & Chan 1990). The inner post-AGB shell radius ($R_{\rm in}^{\rm pAGB}$) is estimated through iterations so that the SED, $T_{\rm dust}$ at $R_{\rm in}^{\rm pAGB}$, and projected 2-D image of the post-AGB shell would be consistent with the observations.

The best-fit SED for the post-AGB shell (thick dashed-dotted line) was then combined with the best-fit SED for the AGB wind shell to construct the total SED for the model. These two best-fit models were derived through independent model calculations because the code is not capable of treating two shells together, and thus the total model is not strictly self-consistent in a sense that the AGB wind shell does not "know" the presence of a post-AGB shell within its inner cavity. However, the post-AGB shell is so optically thin that the input stellar SED (thick dotted line) is virtually unaffected by the presence of the post-AGB shell and thus we conclude that the AGB wind shell model is valid even when the post-AGB wind shell is present.

5. Discussions

5.1. Asymmetric Appearance of the Dust Torus

Our identification of the toroidal dust distribution in the PPN shell is based on the morphology of the mid-IR emission core: there should be two emission peaks, which represent the limb-brightened edges of a dust torus, oriented diametrically symmetric with respect to the nebula center. In reality, however, the mid-IR nebula usually appear somewhat asymmetric because one

peak is brighter and/or more extended than the other. The 11.7 μm image (bottom left in Figure 1) exemplifies such an asymmetry as the imbalance of the peak brightness and size. These asymmetries can be attributed to physical asymmetries of the dust torus, such as asymmetric mass loss (Jura, Chen, & Werner 2000), and an inhomogeneity in the dust distribution (Dayal et al. 1998). It may, however, simply be because of the PSF effect.

Despite the asymmetric appearance of the raw image, the deconvolved 11.7 μm image recovered a highly symmetric morphology of the limb-brightened edges. Comparison with an HST image also shows that the limb-brightened peaks are equidistantly positioned with respect to the central star (Figure 3). Meanwhile, a 2-D projected image of the PPN shell model, which is completely axisymmetric, yielded an asymmetric morphology similar to the observed one after being convolved with the observed PSF image. Thus, no physical asymmetry is required to explain an asymmetric appearance seen in the mid-IR images of the PPN shells, and we argue that our axisymmetric shell model would represent the real PPN shells sufficiently well. This is also supported by the fact that the Keck 12.5 μm image looks more axisymmetric than the MMT 11.7 μm image (bottom frames in Figure 1), which is due to the difference in the PSF shapes: the Keck PSFs appear more symmetric than the MMT PSFs. It is, however, of interest to note that the emission profiles shown in Figure 2 indicates that the NE peak is brighter at lower wavelengths than the SW peak, i.e., the NE peak is warmer than the SW peak.

The origins of axisymmetry in the PPN dust shells, however, are still unclear in spite of a number of possible mechanisms that have been suggested. Such ideas includes the binary interaction (e.g., Mastrodemos & Morris 1999), the magneto-hydrodynamic effects (e.g., García-Segura et al. 2000), and the remnant planetary systems or re-forming accretion disks (e.g., Soker 1997). Whichever the true scenario may be, the axisymmetry generating mechanisms have to be able to create a high equatorial enhancement ($\rho_{\rm eq}/\rho_{\rm pole} = 9$) in the density distribution of the PPN dust shells.

5.2. Dust Size Distribution in the PPN Shell

The resolved mid-IR images placed a rather strict constraint on $R_{\rm in}$. With the energy output (L_*) and $T_{\rm eff}$ of the central star also fairly well-constrained by observations (Kwok, Volk, & Hrivnak 1989; Začs, Klochkova, & Panchuk 1995), $T_{\rm dust}$ is rather tightly fixed unless grain properties are modified. In order to fit the SED, we iterated on the dust size distribution to adjust the energetics in the PPN shell, and the best-fit model suggested the existence of two distinct size distributions: there is a population of larger grains in the superwind shell than the AGB shell. In general, large dust grains are required to cause polarization (Jura 1994), and the best-fit model seems to suggest that one would observe polarized emission from the superwind shell of *IRAS* 22272. Gledhill et al. (2000) imaged *IRAS* 22272 by means of imaging polarimetry and discovered that the polarized emission mainly arose from the elongated shell of dust surrounding the central star. According to their J band image of *IRAS* 22272 (Figure 15 of Gledhill et al. 2000), the extent of the elongated

polarized emission shell is $4'' \times 2''.9$ with $R_{\rm in} = 0''.7$. Our model and the results from the imaging polarimetry agree very well and strongly suggest the presence of a population of larger dust grains in the superwind shell of *IRAS* 22272.

Radiative transfer calculations by Szczerba et al. (1997) yielded $R_{\rm in} = 0''.94$, which is about twice as large as our observed/best-fit value. This difference probably originates mostly from the difference in the size distribution used in the models. Their dust distribution includes a significantly smaller population of grains compared with ours with the absolute minimum and maximum sizes of $5\AA$ and $0.25\ \mu m$. Therefore, their model calculations would have yielded too high $T_{\rm dust}$ and too much IR excess with the observed value of $R_{\rm in} = 0''.5$ because of their use of smaller, more absorption-efficient dust grains, even if we take into account the fact that their spherically symmetric shell structure would provide more dust grains to heat at $R_{\rm in}$.

The derived AGB and superwind mass loss rates ($8 - 40 \times 10^{-7} M_\odot$ yr^{-1}) are about a factor of 2 lower than the previously estimated values from ^{12}CO observations ($9 - 90 \times 10^{-7} M_\odot$ yr^{-1}; Omont et al. 1993). As seen in the model SED, our calculations underestimated the IR excess at around $20 - 40\ \mu m$ due to unknown dust feature carrier species. Such underestimate of the IR excess is directly related to underestimate of dust mass, hence mass loss rates. Therefore, we would consider, also taking into account the uncertainties involved in estimating the mass loss rates from CO observations, that our results are consistent with observations. The previous model calculations (Meixner et al. 1997) suggested mass loss rates that were about a factor of 10 higher than ours. This is primarily because of the inclusion of dust size distribution in our present model calculations. The previous calculations used a single dust size while the present model took into account particles of larger size. This means that the dust shell in the previous model was relatively inefficient in absorbing stellar radiation (i.e., smaller cross sections) and that it took more dust grains to produce the observed IR excess, subsequently resulting in higher mass loss rates. The derived mass loss rates in the present study are reasonable considering the optically *thin* nature of the dust shell. It also shows that a proper consideration of the dust size distribution is required in radiative transfer calculations of the PPN dust shells.

In our model, we simply assumed that the change of the dust size distribution would concurrently take place with the change of mass loss geometry from spherical to axial symmetry. Thus, the choice of $R_{\rm sw}$ and a_0 for the superwind dust shell is crucial in the model fitting. Because $R_{\rm sw}$ is rather difficult to estimate, we need to constrain a_0 through further photometric observations of far-IR, sub-mm, and radio continuum fluxes. Radio continuum fluxes are especially useful because they would yield the power-law like dust emissivity in the Rayleigh-Jeans limit (Knapp et al. 1994), from which we can infer a_0 by a simple analysis (e.g., Jura, Turner, & Van Dyk 2000).

5.3. The Post-AGB Mass Loss

The mid-IR images indicated that there is more centrally concentrated emission in the lower waveband images that could not be accounted for only by the central star (Figures 2 and 3). The radiative transfer calculations showed that, if only the PPN shell was considered, there would be a significant flux underestimate between 5 and 10 μm in the SED (Figure 4) and lack of emission near the nebula center in the lower waveband model images (Figure 5). Our attempt to boost flux at $5-10$ μm by the addition of the post-AGB shell yielded an adequate fit to the observations. The presence of the post-AGB ejecta in the inner cavity of the PPN shell is not entirely *ad hoc* because recent episodes of mass loss have been observationally suggested (Hrivnak, Kwok, & Geballe 1994) and such sporadic mass loss events may be enough to create hot dust grains within the inner radius of the PPN shell. Szczerba et al. (1997) also introduced a hot dust component in their radiative transfer models to increase flux at $5-10$ μm.

These findings all agree to suggest that there seems to be a distribution of dust grains located rather close to the central star. The origins of the hot dust grains are not at all clear: these grains may be a result of a sudden mass ejection (Hrivnak, Kwok, & Geballe 1994) or may simply be a dwindling mass loss continued long after the end of the AGB phase (Szczerba et al. 1997). Our model assumes a scenario in which an ambient mass loss kept continuing after the end of the superwind phase at a rate of $1.6 \times 10^{-7} M_{\odot}$ yr^{-1} (almost equivalent to $\dot{M}_{\rm AGB}$) to be overpowered by a sudden mass ejection presumably occurred 10 years ago at a rate of $\dot{M}_{\rm pAGB} = 5.8 \times 10^{-7} M_{\odot}$ yr^{-1}. These values are comparable to the AGB and superwind mass loss rates and seem to be too high for an "ambient" post-AGB mass loss. These estimates are, however, strongly dependent on $R_{\rm in}^{\rm pAGB}$, the geometry of the post-AGB mass loss, and the dust size distribution in the post-AGB shell. In our model, we simply assumed the same dust size distribution and the shell geometry as in the superwind shell. If we used, for example, a dust size distribution with smaller grains and a spherically symmetric shell geometry, we would needed less amount of post-AGB ejecta to produce the unaccounted IR excess by the PPN shell. This effectively reduces the post-AGB mass loss rates. However, we would not be able constrain these parameters with the currently available observational data. Nevertheless, the existence of some mid-IR emitting material in the inner cavity of the PPN shell seems to require mass loss processes after the end of the AGB phase.

6. Conclusions

We have obtained sub-arcsecond resolution mid-IR images of *IRAS* 22272 at 8.8, 9.8, and 11.7 μm using MIRAC3/BLINC at the MMT observatory and at 7.9, 9.7, and 12.5 μm using MIRLIN at the Keck observatory. The mid-IR core structure was resolved in the 11.7 μm MMT image and at all three waveband Keck images as two emission peaks directly indicating the presence of the central dust torus. The subsequent image analyses suggested that the PPN shell of $R_{\rm in} = 0''.5$ had a rather small inclination angle from the pole-on position.

The 2-D radiative transfer calculations indicated that the mid-IR morphology was adequately reproduced by an axisymmetric dust shell which consists of the superwind shell of 6.0×10^{16} cm and the AGB wind shell of 2.9×10^{17} cm, being inclined by 25° from the pole-on orientation. This fairly equatorially-enhanced ($\rho_{\rm eq}/\rho_{\rm pole} = 9$) dust shell is assumed to be a product of the largely spherical AGB wind mass loss of $\dot{M}_{\rm AGB} = 7.8 \times 10^{-7} M_{\odot}$ yr^{-1} followed by the intrinsically axisymmetric superwind of $\dot{M}_{\rm sw} = 4.1 \times 10^{-6} M_{\odot}$ yr^{-1}, which was terminated about 380 years ago.

The images at lower wavelengths showed very pronounced emission at the nebula center, which the model for the PPN shell failed to reproduce. The best-fit model also indicated the presence of dust gains in the inner cavity of the PPN shell which would seem to have been created after the end of the AGB phase. Our model, based on the observed signature for a sudden mass ejection, suggested that the post-AGB shell would have $R_{\rm in}^{\rm pAGB} = 1.8 \times 10^{15}$ cm after experiencing an ambient mass loss at $1.6 \times 10^{-7} M_{\odot}$ yr^{-1} followed by a post-AGB mass ejection at $\dot{M}_{\rm pAGB} = 5.8 \times 10^{-7} M_{\odot}$ yr^{-1}, which took place about 10 years ago.

The resolved images showed asymmetry in the brightness/size of the two limb-brightened edges of the dust torus. Our image analyses suggest that the PSF effect would be the major factor in causing the observed asymmetry in the mid-IR morphology and no physical asymmetry would be required in the structure of the PPN shell. Nevertheless, the axisymmetric shaping of the PPN shell still requires mechanisms that are capable of inducing a high equator-to-pole density ratio. A population of large particles within the superwind shell was also suggested from the energetics of the dust shell heating in the model calculations. Although our best-fit 2-D model calculations reproduce a number of observed characteristics, proper identification of all the dust features must be accomplished to further improve the quantitative analyses.

We would like to thank the staff at the MMT for their assistance in obtaining the MMT/MIRAC3 data and Karl Stapelfeldt, Ralph Neuhäuser, and Dave Cole for their help in obtaining the Keck/MIRLIN data. We also thank Angela K. Speck for discussions on dust properties and Jun-ichi Nakashima for discussions on a variety of distance determination schemes for the evolved stars. An anonymous referee is also thanked for comments and suggestions. Ueta and Meixner are supported by NSF CAREER Award AST-9733697. MIRAC upgrade and operation are supported by NSF Grant AST-9618850. BLINC construction and operation are supported by the Terrestrial Planet Finder Mission development at NASA's Jet Propulsion Laboratory. This research has made use of the SIMBAD database, operated at Centre de Données astronomiques, Strasburg, France, and the IRAF data reduction and analysis system, which is distributed by the National Optical Astronomy Observatories operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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Fig. 1.— Observed grayscale images of *IRAS* 22272+5435 at 8.8, 9.8, and 11.7 μm obtained at the MMT Observatory (left frames, labeled as "MMT") and at 7.9, 9.7, and 12.5 μm obtained at the Keck Observatory (right frames; labeled as "Keck") with north up and east to the left. The tick marks show relative offsets in arcseconds. Contours are spaced by 10% of the peak intensity with the innermost contour being 90% of the peak. The insets show the corresponding PSF standard stars (β Peg for the MMT observation and β And for the Keck observations) in the same format. Local peak intensities are 15 Jy arcsec^{-2} at 8.8 μm, 14 Jy arcsec^{-2} at 9.8 μm, and 30 and 29 Jy arcsec^{-2} at 11.7 μm. The Keck images were not flux calibrated due to unphotometric sky conditions.

Fig. 2.— Normalized surface intensity profiles of the images sliced along a PA of 55° through the nebula center. The PSF profiles at 7.9 and 8.8 μm are also plotted to show the extension in the peaks.

Fig. 3.— Stellar emission subtracted and Richardson-Lucy deconvolved images at 8.8 (left), 9.8 (middle), and 11.7 μm (right). The displaying conventions follow those of Figure 1.

Fig. 4.— The V band *HST* image overlaid with the 11.7 μm contours following the display convention of Figure 1. Arrows indicate the directions of the elliptical protrusions that are coincident with the "kinked" bicone openings defined by the central dust torus.

Fig. 5.— The spectral energy distribution of the best-fit model: the entire shell system (a thick solid line) consists of the AGB wind shell (thick dashed line) and the post-AGB wind shell (thick dot-dashed line). Photometric data are indicated by a thin dot-dashed line (the *ISO* data) and crosses (various photometric data). Also shown (thin dotted line) is a single dust distribution model having the AGB wind shell dust size distribution ($a_0 = 0.1$ μm) throughout the PPN shell to visualize the peak shift incurred by the change of the dust size distribution. The input stellar SED (thick dotted line) is also displayed to be compared with the stellar peak of the post-AGB wind shell model. In the total model, the best-fit interstellar extinction ($A_{\rm v} = 2.5$) has been applied.

Fig. 6.— The 2-D projected images of the PPN shell model (without the post-AGB wind shell) at 8.8, 9.8, and 11.7 μm following the display convention of Figure 1.

Table 1. Summary of Infrared Observations of IRAS 22272+5435

Date	Camera/Telescope	λ (μm)	Size[1] (arcsec)	PA[2] (arcsec)	PSF Size[3] (arcsec)	Flux[4] (Jy or mag)	Peak (Jy arcsec^{-2})	$F_{\rm star}/F_{\rm total}$[5]
2000 Jun 16	MIRAC3/MMT	8.8	1.3×1.2	57	0.49 ± 0.06	26 ± 1	15	0.06
		9.8	1.4×1.3	59	0.51 ± 0.01	31 ± 1	14	0.04
		11.7	1.7×1.5	56	0.55 ± 0.05	84 ± 4	30, 29	0.01
2000 Nov 4	MIRLIN/Keck II	7.9	1.2×0.8	57	0.37 ± 0.02	···	···	···
		9.7	1.4×1.2	52	0.30 ± 0.01	···	···	···
		12.5	1.7×1.5	51	0.37 ± 0.01	···	···	···
1999 Nov 16	NIRIM/MLO	J: 1.257	···	···	···	5.43 ± 0.15	···	···
		H: 1.649	···	···	···	4.89 ± 0.07	···	···
		K': 2.12	···	···	···	5.10 ± 0.32	···	···

[1]Major and minor axis lengths at 50% of the peak intensity.

[2]Position angle measured counter-clockwise from the North at 50% of the peak.

[3]FWHM of the standard star.

[4]Jy for the mid-IR observations and mag for the near-IR observations.

[5]A flux ratio of the estimated stellar component to the total dust emission.

Table 2. Input and Derived Model Quantities

Parameters	Value		References
	Central Star		
$L_*(L_\odot)$	1.3×10^4		1
$T_{\rm eff}$ (K)	5600 ± 400		2
d (kpc)	1.6		3
ISM $A_{\rm V}$	2.5 ± 0.5		4
	PPN Shell		
	Superwind Shell	AGB Wind Shell	
Inner Radius (cm)	1.2×10^{16} ($= R_{\rm in}$)	6.0×10^{16} ($= R_{\rm sw}$)	
Outer Radius (cm)	6.0×10^{16} ($= R_{\rm sw}$)	2.9×10^{17} ($= R_{\rm out}$)	
$\dot{M}$ ($M_\odot$ yr^{-1})	4.1×10^{-6} ($= \dot{M}_{\rm sw}$)	7.8×10^{-7} ($= \dot{M}_{\rm AGB}$)	
$M_{\rm dust}$ ($M_\odot$)	2.8×10^{-5}	2.5×10^{-5}	
$T_{\rm dust}$ at $R_{\rm in}$, $R_{\rm sw}$ (K)	202	84	
$\tau_{9.8\mu m,\ \rm pole}$	0.001		
$\tau_{9.8\mu m,\ \rm eq}$	0.031		
$\theta_{\rm incl}$[a]	$25 \pm 3°$		
θ_0[a]	$20 \pm 5°$		
PA[a]	$135 \pm 10°$		
$v_{\rm exp}$[a]	10 km s^{-1}		5
Composition	Hydrogenated Amorphous Carbons		6
Dust Size	$a > 10Å$, $a_0 = 10.0\mu m$	$a > 10Å$, $a_0 = 0.1\mu m$	
	Post-AGB Shell		
	Sudden Mass Ejection	Ambient Mass Loss	
Inner Radius (cm)	1.8×10^{15} ($= R_{\rm in}^{\rm pAGB}$)	2.1×10^{15} ($= R_{\rm out}^{\rm pAGB}$)	
Outer Radius (cm)	2.1×10^{15} ($= R_{\rm out}^{\rm pAGB}$)	1.2×10^{16} ($= R_{\rm in}$)	
$\dot{M}$ ($M_\odot$ yr^{-1})	5.8×10^{-7} ($= \dot{M}_{\rm pAGB}$)	1.6×10^{-7}	
$M_{\rm dust}$ ($M_\odot$)	2.6×10^{-8}	2.3×10^{-7}	
$T_{\rm dust}$ at $R_{\rm in}^{\rm pAGB}$, $R_{\rm out}^{\rm pAGB}$ (K)	414	385	
$\tau_{9.8\mu m,\ \rm pole}$	0.001		
$\tau_{9.8\mu m,\ \rm eq}$	0.023		
Composition	Hydrogenated Amorphous Carbons		6
Dust Size	$a > 10Å$, $a_0 = 10.0\mu m$		

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[a]Same for the post-AGB shell.